Design of Synchrotron for Hadron Therapy

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Abstract According to the operation and development of radiation therapy in the world, in order to further promote the radiation therapy of tumour in China, a design of a special synchrotron with two super-periodicity for hadron therapy is presented, including lattice, injection system, RF acceleration and slow extraction of the third order resonance. The synchrotron accelerates the proton beam to 250MeV and the carbon beam to 400MeV/u.

Key words multi-turn injection, lattice, slow extraction, third order resonance

1 Introduction

Nowadays, there is an increasing interest in tumour therapy with hadrons, mainly with protons and heavy-ions, owing to the localization of their energy deposit at the Bragg peak and high relative biological effect (RBE). Three medical centers with carbon therapy have been operated in Germany and Japan and more medical accelerators are in design or construction phase.

The applied research in heavy-ion therapy has been developed at the Institute of Modern Physics (IMP). A new terminal dedicated for hadron therapy has been constructed, utilizing 100MeV/u carbon beam from the SSC cyclotron. Radiation therapy trial is in progress. Based on these developments and experiences, a synchrotron for a clinic accelerator system is designed, with great attention paid to the following considerations:

1) compactness,
2) low cost,
3) high reliability.

The synchrotron is to accelerate carbon ions from 7MeV/u to maximum 400MeV/u and proton from 7MeV to maximum 250MeV, corresponding to the 27cm range in water, and to provide enough quantity of ions for the treatment.

2 The synchrotron

2.1 Lattice design[1]

Figure 1 shows the layout of the synchrotron. The lattice has a super-periodicity of 2 with mirror symmetry within each super-period. By contrast with high super-period, it has three predominances:

1) less sextupoles and quadrupoles,
2) long straight sections,
3) low cost.

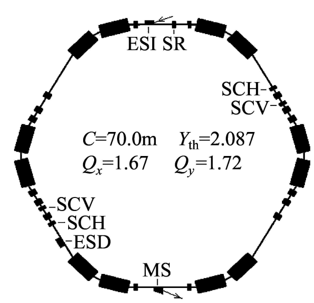

Fig. 1. The layout of the synchrotron.
ESI: electrostatic septum inflector, ESD: electrostatic septum deflector, MS: extraction magnetic septum, SR: resonance sextupole, SCH: horizontal chromaticity sextupole, SCV: vertical chromaticity sextupole.

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Figure 2 shows the betatron and dispersion functions at nominal tunes (1.67, 1.72). The ring has two long straight sections with zero dispersion, accommodating the devices for multi-turn injection and the third-order resonant extraction respectively. Table 1 summarizes the specifications of the synchrotron.

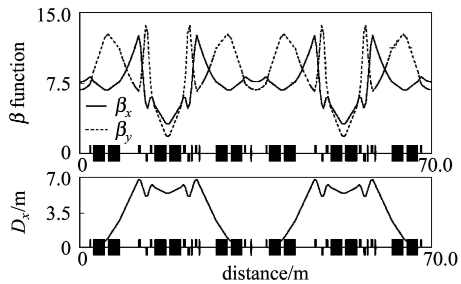

Fig. 2.　The betatron and dispersion functions.

Table 1.　Specifications of synchrotron.

particles	p and C
extraction energy	p: 60—250MeV C: 120—400MeV/u
circumference	70m
super periodicity	2
beam intensity	p: 1×10^{10}ppp* C: 2×10^{9}ppp
injection energy	7MeV/u
Max. dipole field	1.48T
tune Q_x, Q_y	1.67, 1.72
Max. β_x, β_y	12.7, 13.6m
natural chromaticity ξ_x, ξ_y	−1.054, −2.036
Max. dispersion D_x	6.75m
RF frequency(h=3)	1.5—9.2MHz

*particles per pulse.

The horizontal aperture required for the carbon beam injection ranges from −64.8mm to 35.0mm, taking account of a maximum horizontal closed-orbit margin (±10mm), $\pm\sqrt{5}\sigma$ beam envelope with full momentum spread dp/p=0.5% (±49.8mm) in focusing quadrupoles and a further 4—5mm collimation margin.

The vertical aperture is ±32.7mm in defocusing quadruples, including vertical closed-orbit margin (±7.5mm) and $\pm\sqrt{5}\sigma$ beam envelope (±20.2mm) and a further 5mm collimation margin. The vertical aperture is ±32.0mm in dipole magnets, including $\pm\sqrt{5}\sigma$ beam envelope (±19.5mm) and vertical closed-orbit margin (±7.5mm) and ±5mm collimation margin.

2.2　Injection system

Fully stripped carbon particles from a linac injector will be injected into the ring by multi-turn injection method. As Fig. 3 shows, the injection system includes four fast bump magnets, one magnetic septum and one electrostatic septum inflector (ESI). Bump magnets form a 40mm bump orbit from the central orbit. The beam is injected in the middle of the long straight section. ESI is located at 45mm from the central orbit. The emittance of injection beam is less than 10πmm·mrad.

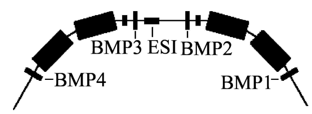

Fig. 3.　Layout of injection system.

Figure 4 shows the aperture occupied by the beam at injection just after the RF trapping. The full momentum spread of the beam is 0.005 and the relative momentum offset from the central orbit is −0.002 to push the beam to the inside in dispersion regions with 10mm closed-orbit margin and 4mm collimation margin between the beam and the electrostatic septum. The horizontal and vertical 1σ emittance is 6.0πmm·mrad respectively. The beam edge (2dim.) is $\pm\sqrt{5}\sigma$.

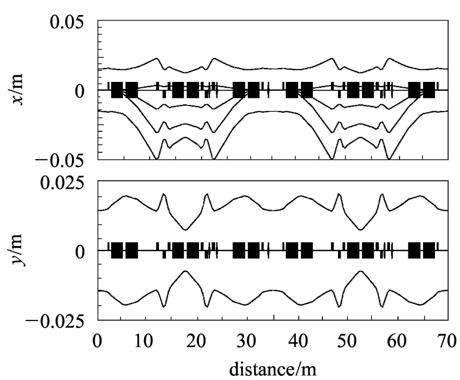

Fig. 4.　Envelopes of the carbon ion beam at injection after RF trapping.

2.3　RF acceleration

Beam is captured and accelerated by a RF accelerating cavity. The exciting current of the bending and quadrupole magnets is synchronized with the variation of beam energies. The RF frequency keeps 3 harmonics of the revolution frequency during acceleration process. For the designed beam energy at injection and extraction, the frequency of the RF accelerating system will cover the range from 1.5MHz to 9.2MHz. The maximum ramping speed of the main dipole magnets is 3.0T/s, corresponding to an acceleration time of 0.433s and an acceleration voltage of at least 900V up to the maximum extraction energy of 400MeV/u.

2.4 Extraction system[2—4]

In order to provide rational dose and sufficient time for tumour therapy. A third order resonance extraction system is used with Q_x=5/3. An electrostatic septum deflector ESD (<60kV/cm) is located in a dispersive straight section ($D_x > 0$, $D'_x < 0$) with a magnetic septum deflector (0.5T) located in the achromatic straight section following the ESD. Three sextupole families are used. A single sextupole is located in the other achromatic straight section before ESD for resonance excitation. The other two sextupole families are located in diametrically opposite positions in the ring for chromaticity correction. Due to the symmetry of two, the ring can be split into two halves with identical sequence of magnetic elements. The dispersion and betatron on the opposite sides of the ring are identical. Assuming the strength of the resonance sextupole is S_1, the strength of the chromaticity sextupole is S_2. Consider now the chromaticity effect of resonance sextupole and the resonance effect of chromaticity sextupole.

The resonance effect of chromaticity sextupole

$$S^2_{\rm Rvirt} = \left(S_2\cos(0)+S_2\cos(3Q\pi)\right)^2 + \left(S_2\sin(0)+S_2\sin(3Q\pi)\right)^2 \approx 0\,.$$

The chromaticity effect of resonance sextupole

$$\Delta Q_x = \frac{l_s}{4\pi}\beta_x D_x(c\cdot S_1)=0\,,$$

$$\Delta Q'_z = \frac{l_s}{4\pi}\beta_z D_x(c\cdot S_1)=0\,,$$

and c is constant. So the chromaticity sextupoles and resonance sextupole act respectively and do not affect each other.

The electrostatic septum is located at 35mm apart from the central orbit. The spiral pitch is 0.06mrad and the spiral step into the septum is 10mm, satisfying the Hardt condition. The angle of the extracted particles is 0.09mrad for dp=0. Fig. 5 shows a phase space (a), (b) and separatrices (c), (d) simulation of extraction beam. The horizontal emittance is 7.03πmm·mrad at 120MeV/u, and the extraction tunes Q_x, Q_y are 1.667, 1.72. Fig. 6 shows the last 3-turn orbits before interception by the electrostatic septum in the ring for the extracted carbon beam. The normalized emittance is 3.68πmm·mrad. The momentum spread of extracted beam is −0.093%. There are two orbits, one for zero-amplitude particles that are exactly on resonance and the other for particles with maximum emmitance at extraction energy E=120MeV/u.

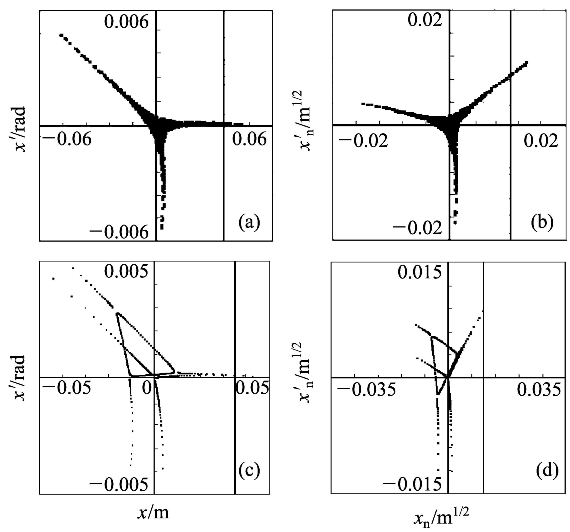

Fig. 5. Phase space (a), (b) and separatrices (c), (d) representation of extraction at the electrostatic septum.
(a) unnormalized; (b) normalized; (c) unnormalized; (d) normalized.

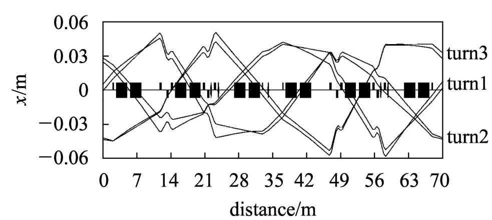

Fig. 6. The last 3 turns of the separatrics for the extracted carbon beam.

As the extraction beam is made to the outside of the chamber and the ‘waiting’ stack is in the inner half of the chamber. In order to ensure a balanced growth of the separatrices, the resonance is positioned at the chamber centre. Thus in a synchrotron employing resonant slow extraction, the horizontal aperture is determined mainly by the extracted beam separatrices while the vertical aperture is determined by the injection beam. The requirements of horizontal physical aperture for the carbon beam are −68.7mm to 66.1mm:

1) −68.7mm (inside aperture) = −58.7mm (inside excursion) + −10.0mm (closed orbit margin),

2) 66.1mm (outside aperture) = 56.1mm (outside excursion) + 10.0mm (closed orbit margin).

Within this aperture, particle trajectories do not interfere with the septum of the injection electrostatic inflector (ESI).

3 Summary

The synchrotron ring is designed conceptually for the carbon therapy facility, the circumference of the ring is 70m, and sing turn injection and slow extraction of resonance are employed, further optimization work is in progress. At last, the free program Winagile is used for the design of synchrotron.

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治癌离子同步加速器的物理设计

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摘要 根据国际放射疗法的现状和发展, 为了进一步提升国内的肿瘤放射疗法, 研究设计了 1 台由两个完全相同的超周期组成的治癌专用离子同步加速器, 包括LATTICE、多圈注入系统、RF加速及三阶共振慢引出系统. 该加速器可以把质子加速到250MeV及碳离子加速到400MeV/u.

关键词 多圈注入 磁聚焦结构 慢引出 三阶共振

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